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Integration of Microwave Plasma Ignition Into A Multi-Fuel Engine

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14. ABSTRACT
The purpose of this effort was to demonstrate the successful integration of a Quarter-Wave Coaxial Cavity Resonator Plasma Igniter into a multi-fuel engine. The grantee successfully accomplished the objective by demonstrating successful engine operation with both gasoline and jet fuel. Microwave frequency stimulation of the highly ionized combustion mixture, and generation of reactive oxygen species can potentially result in more complete combustion, preventing in-cylinder build-up of deposits and achieving improved fuel economy. It is expected that with the addition of more effective microwave electronics control, this type of ignition system can easily surpass conventional spark ignition performance and capabilities. Continued work would seek to eliminate the transfer hurdles, to compact and optimize the electronic control to take advantage of the microwave plasma plug's theoretical performance superiority.

15. SUBJECT TERMS
Microwave ignition, multi fuel engine, Quarter-Wave Coaxial Cavity Resonator Plasma Igniter

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1.0 INTRODUCTION

The Quarter-Wave Coaxial Cavity Resonator Plasma Igniter (QWCCR) is a novel use of a microwave plasma source as a spark plug replacement. The QWCCR is a highly efficient impedance transformation device that can step up the electrical potential of highly reactive microwave energy to potentials that are capable of heating and ionizing gases, and igniting air fuel mixtures.

Laboratory tests of the QWCCR have demonstrated repeated cylinder ignition of an internal combustion engine using a QWCCR however, precise ignition timing and associated microwave electronics suitable for incorporation into application specific engine use need considerable development, the emphasis of this program. High temperature, high pressure QWCCR plugs constructed of suitable materials, such as low expansion ceramics, need to be designed, fabricated and integrated into an engine cylinder for a specific end-use application.

Plasma ignition for combustion engines will potentially allow the ignition of problematic mixtures, the reduction of regulated pollutants, and may have other performance benefits. The energized volume of the QWCCR can be larger than a conventional spark plug spark, thus reducing the thermal point loading that results from a spark gap. Additionally, the nature of the microwave discharge is to pump energy into the cylinder cavity prior to the ignition as a way to energize the fuel/air mixture and to aid in combustion. Reduced erosion of the single plasma electrode is another expected benefit of the plasma plug. Complete engine integration and subsequent field testing of a plasma ignition system will provide a commercially viable system that will enhance the future value of the total engine market in addition to the application-specific needs addressed.

Plasma ignition for combustion engines may allow for reduction of regulated emissions such as NOx and may have other benefits. Since the energized plasma volume of the QWCCR is generally larger than a conventional spark plug spark, improved ignition efficiencies should result. An enlarged plasma volume is particularly suitable for ultra-lean burn and stratified charge engine environments. Reduced erosion of the single plasma electrode is another expected benefit of the plasma plug. Completion and subsequent testing of an automotive plasma ignition system will allow experimental verification of these assertions.

2.0 STATEMENT OF WORK

The statement of work for the project titled "Integration of Microwave Plasma Ignition into a Multi-Fuel Engine Phase II" will be the successful testing of the ignition plug in a West Virginia University (WVU) test engine using gasoline and jet-A fuel. This project is divided into three tasks. The first task will be to refine the design of a robust plasma igniter prototype suitable for in-cylinder environment. The second task will be to improve the design/construction and/or acquire a microwave generator/microwave switching circuitry to deliver precise microwave pulses to a plasma igniter to cover this fuel range application as needed. The last task in this phase will be to test the plasma plug in a laboratory test engine with suitable firing electronics and ignition control to test engine operation with jet-A and gasoline fuels. After these three tasks have been completed, a final report will be submitted.

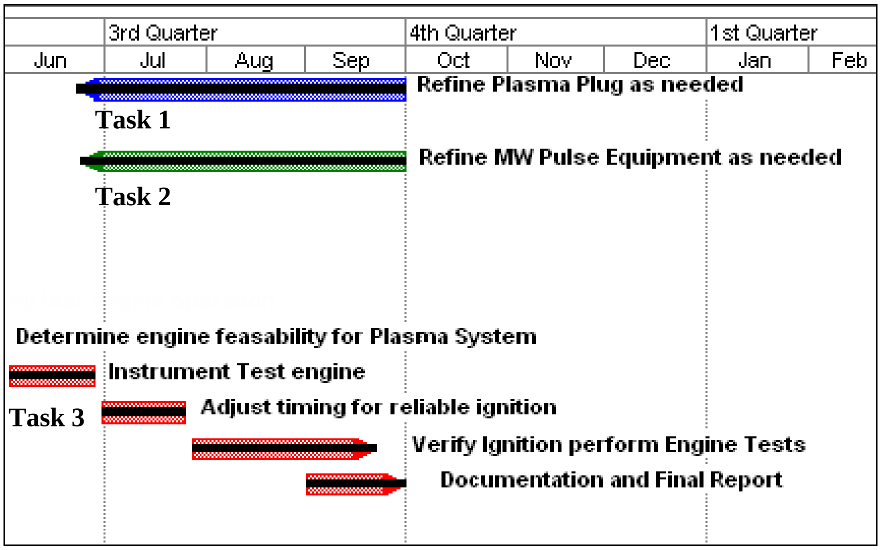

Figure 1. Timeline for Tasks 1,2,3

Task 1, the refinement of the design of a robust plasma igniter prototype suitable for an in-cylinder environment was completed as shown in blue in figure 1. The current prototypes used have not shown significant issues during the engine testing that was performed. The ceramic seal and impedance matching structure held up well during testing, and soot deposits did not impede the plugs performance to any significant degree.

Task 2, the improvement of the microwave generation and pulse equipment to deliver precise microwave pulses to the plasma igniter for the fuel range as needed was completed. For the initial testing performed, the magnetron pulse microwave circuit was adequate. Future microwave electronic developments should focus on frequency compensation and on maximizing energy delivery. This task is show in Figure 1 in green.

Task 3, testing of the plasma plug in a laboratory test engine with suitable firing electronics and ignition control to test engine operation with jet A and gasoline fuels, was completed. Additional work was then completed on a fuel injection system and a preliminary investigation into fuel-air ratio effects, some cold start tests were performed all outside of the scope of this project. The results are detailed below.

3.0 OVERALL PROGRESS

The overall program for Phase I and II are completed. The results and conclusions for the work related to Phase II are:

3.1 Plasma Plug

Phase I development and Phase II testing of the plasma plug revealed that it is critical to properly engineer the interface to the coaxial cable delivering the microwaves so breakdown can be avoided at this interface. Failure to do so will result in microwave plasma generation at the interface and subsequent destruction of the dielectric and conductors. The microwave field strengths are the largest on the surface of the connector center conductor where discharges would occur in inadequate designs. Minor impedance mismatches at the interface and heating of the plug once installed and operated in an engine block, increased both the field strengths and lowered the breakdown threshold resulting in the destruction of the connector's polytetrafluoroethylene (PTFE) dielectric.

In the beginning of phase II this problem was solved by choosing a suitable connector with a large center conductor. The N-type connector design has a suitably large center electrode and was integrated into the plasma plug design. Additionally, the PTFE dielectric commonly used in such connectors was replaced with a suitable ceramic. Initial uses of MACOR™, a machinable mica-glass ceramic, as the dielectric showed promise, but thermal expansion of the metal and available machining precision, left lower dielectric strength air gaps between the ceramic and center conductor with subsequent breakdowns occurring. These breakdowns were destructive to the metallic center conductor and the formation of plasma in the transmission path effectively shorted out further microwave power delivery to the igniter.

Changing the dielectric to a castable ceramic with appropriate dielectric properties then sealed out any air gaps, provided high temperature stability, and reliably sealed the plug to maintain in cylinder compression. Careful shaping of the plasma igniter's interior was performed to maintain a high resonant quality factor and to aid microwave plasma formation at the discharge tip. Minor soot deposits over the interior of the cavity surfaces did not affect the plug's performance in any significant way. Both quality factor and resonant frequency of the plasma plug remained stable.

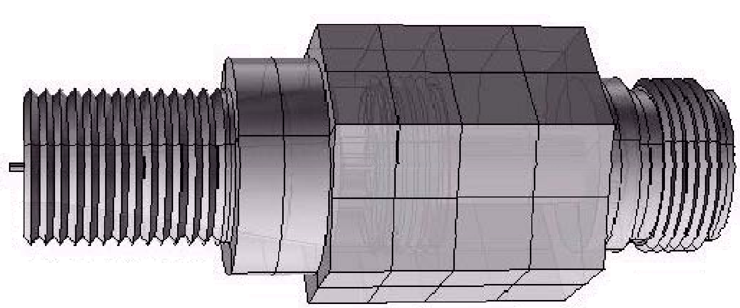

Figure 2 Microwave Plasma Plug with N-Type Connector

3.2 Microwave Pulse Supply

For the microwave plasma ignition to be practical, a reasonably robust microwave supply capable of operating in an engine environment is needed. As a first step toward this device, the laboratory traveling wave tube amplifier was replaced with a commercial low cost microwave oven magnetron as the microwave source. Magnetrons are efficient and compact microwave generators that allow thermal electrons to give up their kinetic energy to microwave resonant cavities as they follow magnetically guided curved paths inside the magnetron. The kinetic energy is obtained as the electrons fall through an applied electric potential.

In a microwave oven this potential, applied between the heated cathode and the anode wall of the cavities, is provided by the 60 or 120 Hz half-wave rectified mains input which is stepped up to 4-6kV. The generated microwaves are radiated into the interior of the microwave oven. Instead of this semi continuous application of radiated microwaves, the plasma ignition system requires precisely timed pulses delivered down a coaxial cable to the plasma igniter.

To accomplish this, the magnetron antenna was adapted to a coaxial N-type connector via a piece of rectangular waveguide one wavelength long and shorted at both ends. The coaxial probe pickup and the magnetron antenna were inserted into this waveguide spaced approximately ½ wavelength apart and each about a ¼ wavelength from the shorted ends of the waveguide. The exact positions were adjusted for the best energy transfer and impedance match. The adjustments were made with the help of a high power attenuator and a spectrum analyzer.

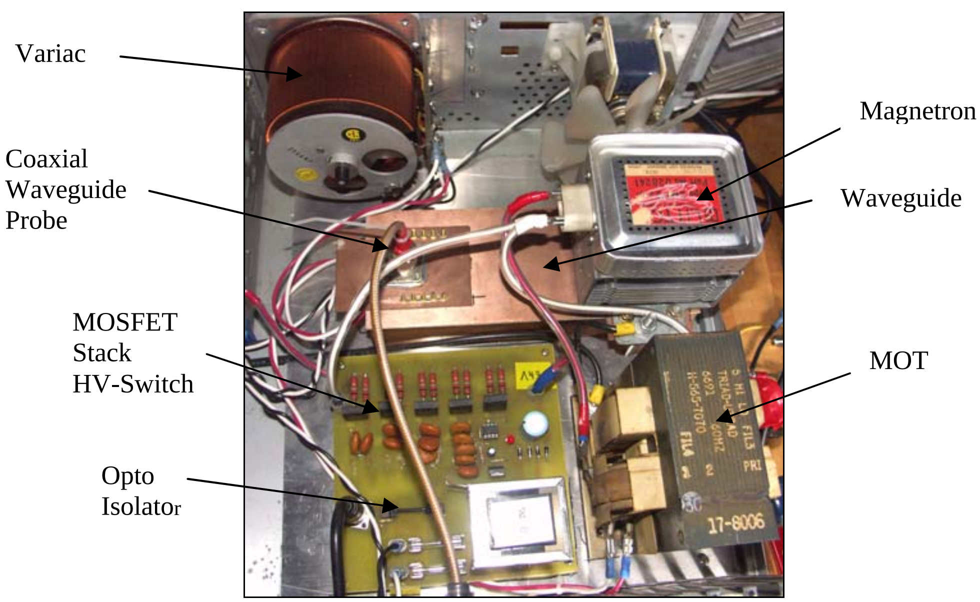

Figure 3 Magnetron Microwave Pulse Supply

The microwave oven high voltage circuit, consisting of a microwave oven transformer (MOT), rectifiers and level shifting capacitors, was modified to dc charge a capacitor to approximately negative 4kV, as required by the magnetron cathode. The exact voltage level was controlled by a Variac transformer. At appropriate times during the engine cycle, the high voltage was then applied to the magnetron cathode via a stack of MOSFET transistors. Switching of these transistors allowed the generation of sharply defined microwave pulses by the magnetron. The MOSFET stack was controlled through an opto-isolated microcontroller output.

The microcontroller allowed for adjustment of ignition delay and pulse duration. The pulse widths generated with this setup were adjustable from 2ms down to 100μs and produced microwave pulses with peak power levels of 58dBm. In-cylinder ignition was achieved with pulse widths as low as 200μs, but for reliability the pulse width was set at 500μs. This microwave source could be further compacted and modified to run in a 12Vdc system, or an alternative microwave source that is already further developed could be adapted to the plasma igniter. The microwave oven magnetron source did supply adequately powerful microwave pulses to drive the igniter for the purpose of engine testing.

3.3 Briggs and Stratton Engine Instrumentation and Testing

Phase I work showed that the plasma igniter could function as an ignition source with similar energies to those of standard sparkplug. Phase II work was focused on operating in a real engine environment using multiple fuels, specifically gasoline and jet fuel. The test engine used was a Briggs and Stratton 1450 Intek (8hp) 305cc 8.5:1 CR OHV 4-stroke engine. Use of a single cylinder engine was simpler as it did not require a microwave ignition system distributor or the construction of additional microwave power supplies. The stock engine was outfitted with a timing wheel and ignition signal pickup/timing circuitry and dual fuel tanks for gasoline and jet fuel. Initial experimentation at the beginning of phase II showed that once warmed up on gasoline, the engine was able to run and start on both gasoline and jet fuel using conventional spark ignition or plasma ignition. However with a carbureted fuel system, control over the fuel/air mixture, a key parameter in ignitability, was not possible. This is because carbureted systems are not programmable like fuel injected systems.

In order to overcome this, the engine carburetor was removed and a fuel injection system was installed. This fuel injection system, controlled by an after market Megasquirt EFI controller, required various other auxiliary components such as an exhaust gas oxygen sensor, fuel pump, fuel injectors, and the design and fabrication of a fuel rail and intake system.

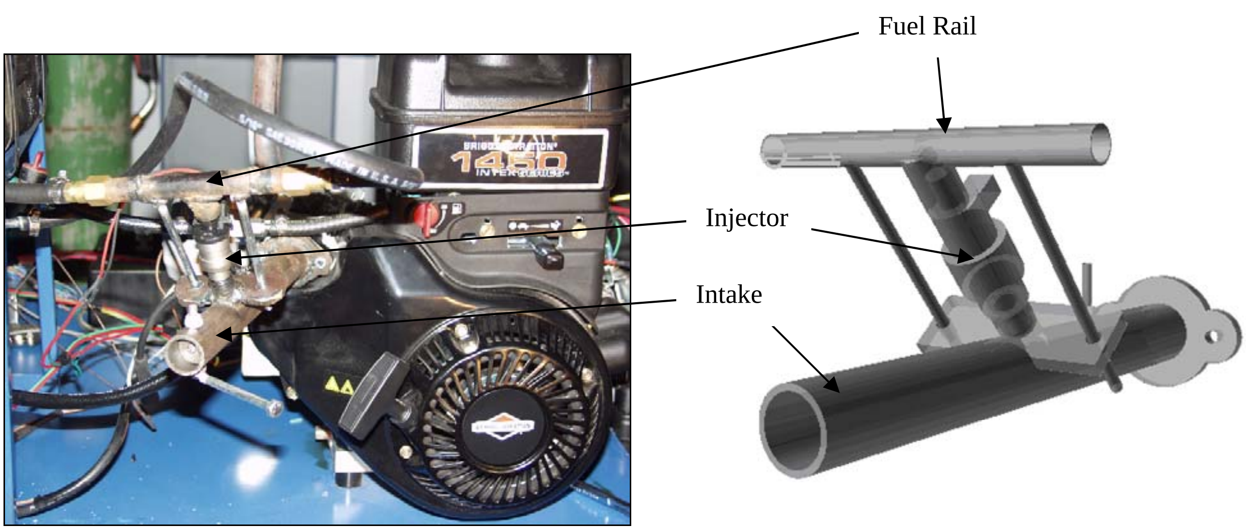

Figure 4. Fuel Injection System

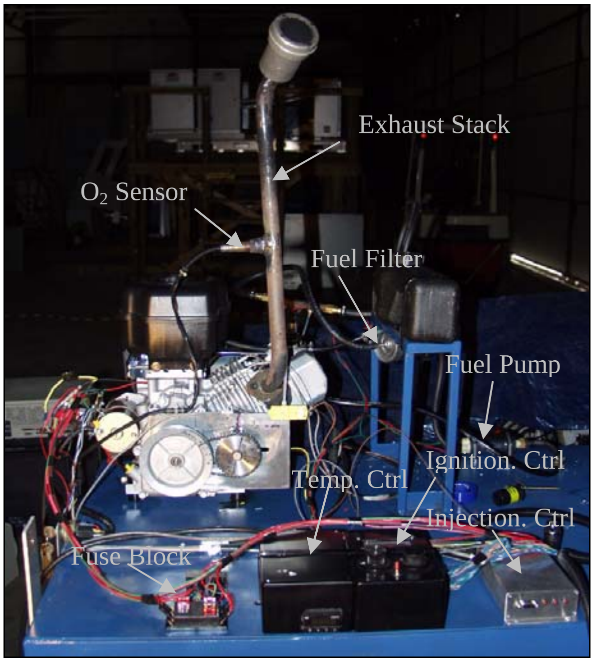

Figure 5. Auxiliary Engine Modifications

Figure 6. Installed Plasma Igniter

After engine modifications, the system was capable of starting and running on both gasoline and jet fuel. The fuel injection signal was coordinated via the same pulse signal that controlled the microwave ignition system. Preliminary data was taken for both a spark plug and the plasma ignition system as the fueling was adjusted, using no external engine loading, but just throttle loading. Both plasma and spark followed similar trend, for gasoline. These preliminary data are shown in Figure 7.

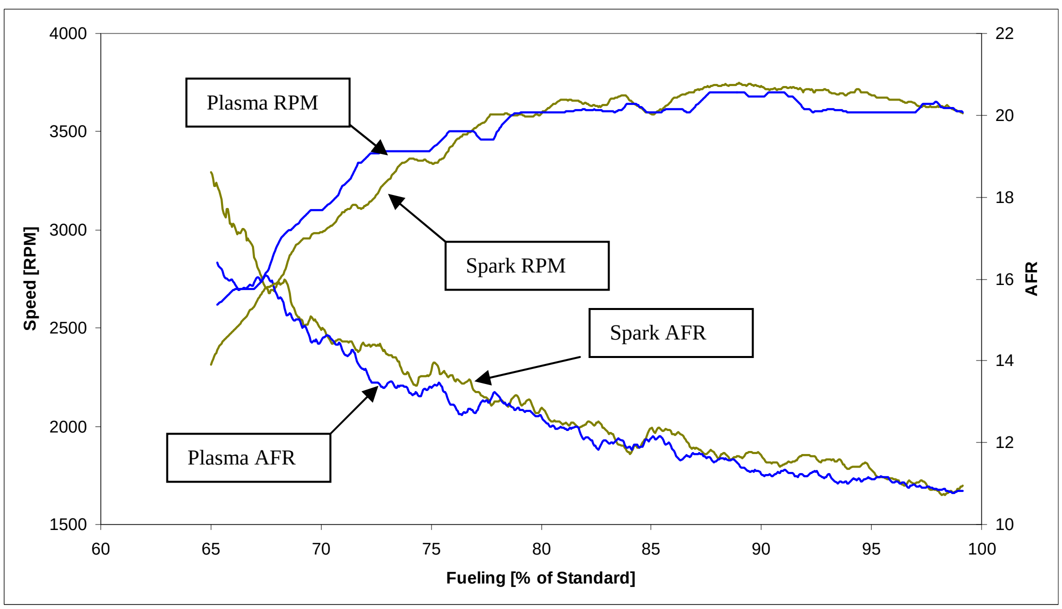

Figure 7 Preliminary throttle loading data for gasoline

The similarity between plasma and spark ignition shown in Figure 2 is expected, with gasoline under "no-load" condition. It is expected that a more pronounced difference would be seen if an external load were to be applied to the engine. Proper tests under loaded conditions will require engine dynamometer setup.

Another set of tests that were performed investigated the cold start capability of the plasma plug relative to a conventional sparkplug. These tests determined the temperatures at which the engine started on spark and plasma ignition systems. The series of tests were run under controlled conditions. The engine was mounted on a test stand, without loading, and minimal throttling, so that all starts were attempted at a 'high idle' condition.

To find the cold start limit of jet fuel for both spark and plasma ignition sources, a range of testing temperatures were required. During the month of September 2008 in Morgantown, WV, the testing facility experienced temperature fluctuations between 50-90°F. After a successful start at 50°F and the lack of very cool days, artificial cooling was required in order to establish the cold start limit. A cold cell consisting of two layers of R5 foam insulation was constructed around the test engine and dry ice was used to provide artificial cooling. This reduced the cell temperature to well below the engine's cold start limit. The desired temperature ranges were achieved by cold soaking the engine and then allowing it to warm in a semi-insulated environment until the head and oil temperatures reached the desired level. This was done to avoid potential uneven warming in an un-insulated environment. The intake air for these tests was taken from outside the cell to avoid any chemical effects of the dry ice, but due to the length of the intake tract used the bulk temperature of the air was near that of the engine by the time compression took place.

Testing had to be spread out over several days to allow adequate cooling time between tests and so that no temperature gradients exited in the engine or engine block. The testing started with a lean mixture and the increased fueling until the engine either fired or it was determined that ignition could not be achieved at that particular temperature. This procedure was to prevent flooding of the engine with fuel and fouling the igniter. The test procedure followed for data collection is outlined below:

- Check that block temperature is within 5°F of ambient air temperature.
- Turn on fuel and check that the jet fuel tank is selected. Connect battery and turn on switches and ignition.
- Cycle fuel pump for 5 seconds to build proper fuel pressure.
- Set fueling to initial lean value of 10.0[1].
- Engine is cranked 15-20 seconds. If engine starts, let run 1 minute, and then shut off, and record the number of cranks, fueling, and temperature data.
- If engine does not start, increase fueling and retry. If no ignition, continue this to increase fueling up to a maximum value of 25. If fueling of 25 is reached without starting, crank engine for three 15-20 second attempts, waiting 30 seconds in between. If at this time the engine has not fired, record a no start condition.
- After all tests, switch fuel to gasoline and run for 5 minutes at a fueling value of 12.0 and speed of 3400RPM to clear any residue from the cylinder.
- Turn off fuel and ignition, disconnect battery, and turn off safety switches.
- Let cool at least 3 hours before next test.

[1] Fueling values are based on constants used within the engine control unit's tuning program.

Using this methodology, data was collected over a period of several days in order to experimentally determine the cold-start limit of jet fuel for this engine setup.

Upon completion of testing, results were tabulated, and a comparison was made with respect to the cold start limit of both spark-ignited and plasma-ignited jet fuel. The data reduction yields a cold start limit of 47-50 °F for the convention spark plug and 57-60 °F for the plasma plug, as shown in Figure 8.

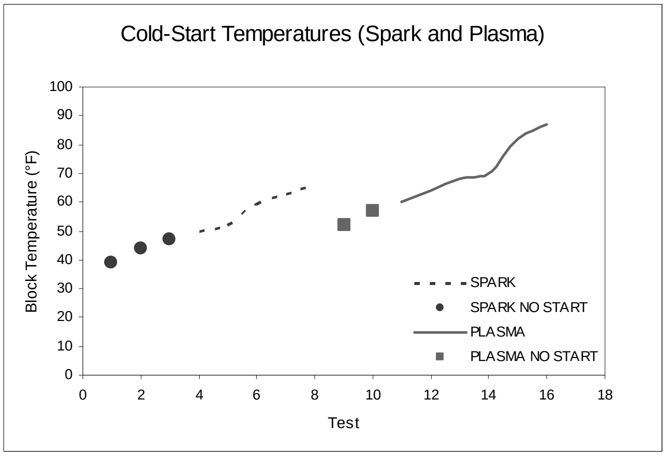

Figure 8. Cold start testing results

The correlation between the required fuel to start and temperature was also examined, as richer mixtures are easier to ignite in cold conditions, so the fuel required was an indication of ignition suitability. It can be seen from Figure 9 , which illustrates this relationship, that the spark plug generally required a leaner mixture to achieve ignition.

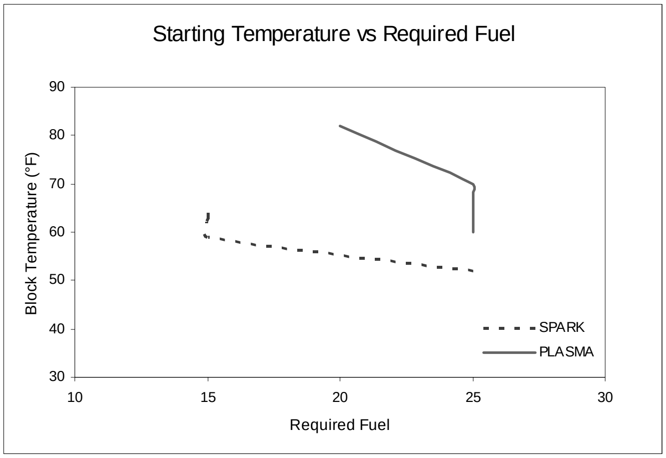

Figure 9. Cold start fueling curves

The results for the cold start testing show that the current plasma ignition system does not perform as well as the original equipment spark plug system. It is thought that this is the result of the current low power delivery to the plasma plug. The presently implemented plasma system also does not correct for the impedance mismatch and the frequency shift caused by the formation of the plasma kernel. Figure 10, a power delivered measurement take during the initial ignition experiments, illustrates the effect of this on power delivery by the microwave plasma.

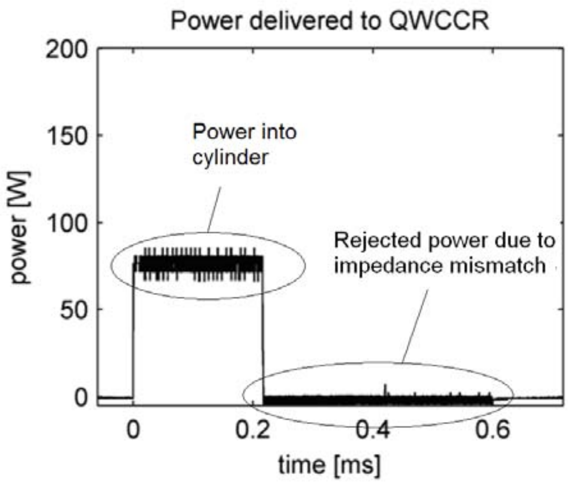

Figure 10. QWCCR power curve

4.0 CONCLUSION

Clearly the prospect of the microwave plasma plug serving as a viable internal combustion engine ignition source, for both gasoline and jet fuel has been confirmed. Further, the results of the preliminary tests that were performed supplemental to the scope of the current phase show that the plasma plug provides nearly comparable capability to a conventional spark based system with respect to cold start and lean burn despite its current energy transfer handicap. The plug itself is potentially capable of transferring an order of magnitude more energy into the cylinder than is accomplished with the current microwave driving electronics and control. The goals for phase I and phase II, to demonstrate that the microwave plasma plug could serve as an ignition source and operate in an engine using multiple fuels have been met. Methods to increase the energy transfer by compensating for the frequency and impedance shift caused by the plasma kernel formation have already been explored experimentally.

Additionally, the plasma plug electronic control can tailor the plasma not only for initial ignition. Due to the high controllability and modulation capability during the plasma on-time it is feasible to assist in the combustion process, not only at the beginning, but throughout the entire combustion process. Microwave frequency stimulation of the highly ionized combustion mixture, and generation of reactive oxygen species can potentially result in more compete combustion, preventing in-cylinder build-up of deposits and achieving improved fuel economy.

It is expected that with the addition of more effective microwave electronics control, this type of ignition system can easily surpass conventional spark ignition performance and capabilities. Continued work would seek to eliminate the transfer hurdles, to compact and optimize the electronic control to take advantage of the microwave plasma plugs theoretical performance superiority.

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